COMMERCIAL TESTING AND OPTIMIZATION STUDIES OF THE SURFACE PASTEURIZATION PROCESS OF CHICKEN[1]

MICHAEL KOZEMPEL[2], NEIL GOLDBERG, E. RICHARD RADEWONUK and O. JOSEPH SCULLEN

U.S. Department of Agriculture
Agricultural Research Service
Eastern Regional Research Center
600 E. Mermaid Lane
Wyndmoor, Pennsylvania 19038

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ABSTRACT

The performance of the surface pasteurization process to reduce the bacteria levels on the surface of chicken was tested on carcasses received from federally inspected commercial processing plants. These tests were made with carcasses that had been chilled and shipped overnight with ice packs. The tests and follow-up experiments showed the visceral cavity was not treated as effectively as the outside. A second series of tests with chicken halves which eliminated the difficulty with the cavity, produced significant kills in E. coli, *coliform, and total aerobic plate counts. Further research with chicken purchased at the supermarket established optimum process conditions as initial vacuum of 0.1 s, steam at 138C for 0.1 s, and final vacuum of 0.5 s. At these conditions, for half carcasses, bacteria kills for* E. coli, *coliforms, and APC generally ranged from approximately 0.5 to 1.0 log cfu/mL. The process is being modified to assure adequate treatment of the cavity.*

INTRODUCTION

The safety of our food supply has come under close scrutiny. The issue has spread across most foods, including fruit juice, vegetables, and meat. President Clinton (1997) called for increased research into assuring the safety of the food supply. New regulations have established Hazard Analysis Critical Control Point (HACCP) regulations for most meat processors, including the poultry industry. There has been much discussion how to improve food safety.

[1] Mention of brand or firm names does not constitute an endorsement by the U.S. Department of Agriculture above others of a similar nature not mentioned.

[2] To whom correspondence should be addressed: E-mail: mkozempel@arserrc.gov. Tel: (215) 233-6588; Fax: (215) 233-6795.

Pathogenic bacteria are found on the surface of sound meat. An innocuous process (Morgan *et al.* 1996a, b) has been under development that kills bacteria on the surface of meat through the combination of vacuum and steam. Steam temperatures are sufficient to kill bacteria if the steam can reach the bacteria.

Bacteria lodge in pores on the surface of poultry with a thin film of air covering the bacteria and pores. The pore size effectively restricts the entrance of sterilizing liquid from contacting the bacteria in the pores. However, a gas can reach into the pores if the thin film of air is removed and the mean free path is sufficiently short. A thorough discussion of the theory was presented in Morgan *et al.* (1996a). In the Morgan process (Morgan *et al.* 1996a, b), this air is removed with a quick exposure to vacuum (0.1 s). A short burst of steam (0.1 s) followed by another vacuum cycle (0.5 s) kills bacteria and cools the chicken to prevent thermal damage. The entire process takes place in less than 1 s, within the rate of most poultry processing lines.

The effectiveness of the treatment depends on the ability of the pasteurizing steam to contact the bacteria in the pores of the chicken carcass. Originally, the unit was intended for installation after the chill tank. However, industry's opinion was that the best location is before the chill tank. At this location in the process line, the carcass is without head, feathers, internal organs, and feet, is still warm, and the pores are open. After the chill tank, the pores should be constricted, partially restricting but not preventing access to the bacteria. Therefore, treating the chicken before the chill tank should give better bacterial kills and reduce cross contamination in the chill tank.

Previous research (Morgan *et al.* 1996a, b) showed that the process will kill *Listeria innocua*, a nonpathogenic indicator organism, when this organism is inoculated onto the surface of the chicken, which is then processed. *L. innocua* was chosen as the test organism because it is nonpathogenic and more thermally resistant than *Salmonella*, *Escherichia coli*, and *Campylobacter*. However, bacteria inoculated on the carcass surface may not respond to treatment in the same manner as bacteria already present as natural flora. Therefore, the objectives of this study were to test and optimize the surface pasteurization process using poultry samples directly from commercial processing plants and from supermarkets using no inoculated bacteria.

MATERIALS AND METHODS

The performance requirements of an in-line surface pasteurizer are to accept samples individually and to enclose them in a chamber to evacuate that chamber; to treat it in that closed chamber with steam; to cool it with vacuum; and finally to eject it into a clean environment. Each sample must be treated individually in order to avoid the shielding and cross-contaminating caused by the soft surfaces

of several samples pressing together. The simplest design, one chamber, an eight inch ball valve, in one rotor was designed and constructed.

The typical broiler carcass observed was 180 mm high, neck to breech; and 150 mm wide, wing to wing. The height was measured as though the bird were sitting with legs forward. This height to width ratio of 1.2 was rather constant. An arbitrary safety factor of 1/3 was used for the dimensions of the product chamber to assure adequate capacity for all broilers. Therefore, the dimensions were assumed to be 133% of the observed dimensions of the sitting carcass. A cylindrical chamber for a broiler carcass should therefore be about 200 mm in diameter, 240 mm deep. Such a chamber is provided by an eight inch ball valve.

To admit vacuum or steam into the closed chamber, two opposed 200 mm holes were bored through the stator at right angles to both the axis of rotation of the ball and to the centerline of the open chamber (Fig. 1). Two gas valves are close coupled to these 200 mm ports and consist of a flat disk rotating against an inlet header, which holds PEEK (polyetheretherketone) seals. Each disk contains two holes, which when stopped at one of the ports in the inlet header permits gas to flow into the treatment chamber. Multiple holes reduce the rotor angular movement necessary for valve action and increase the cross sectional area for gas flow. Each disk is programmed independently and moved by its own servo motor. The servos were 50 joule units, capable of high acceleration and deceleration.

In order to expose all exterior surfaces of the test specimen to treatment, a screen was installed at the midpoint of the product valve to hold the sample. The steam generator was charged with deionized water, which was boiled for 30 min for deaeration. The vacuum receiver was adjusted to 70 mbar and its condenser coil cooled to 4C.

Each sample, Cornish hen, Cornish hen cut in half, fryer cut in half, or drumstick, was manually inserted into the treatment chamber of the surface pasteurizer. The ball valve was rotated 90 degrees, either pneumatically or with a servo, to seal the chamber from the outside atmosphere. Operation of the ball valve was computer controlled. The platter valves rotated to expose the sample to vacuum, then steam, and then vacuum again. Process variables were vacuum times, steam temperature and time. After treatment, the ball valve rotated back 90 degrees to expose the sample to atmosphere. The sample was aseptically removed manually after treatment. The extent of cooking was visually judged subjectively immediately after treatment. The onset of cooking was obvious, marked by the whitening of the exposed flesh or shrinkage of the skin.

Depending on the objectives of the individual experiment, chicken samples were either Cornish hens, Cornish hens cut in half, fryers cut in half, or drumsticks. The first series of tests utilized Cornish hens acquired from a federally inspected commercial processing plant after the chill tank. The second series of tests utilized fryers cut in half acquired from a federally inspected

commercial processing plant before the chill tank. These commercial process plant samples were shipped overnight with ice packs to prevent spoilage.

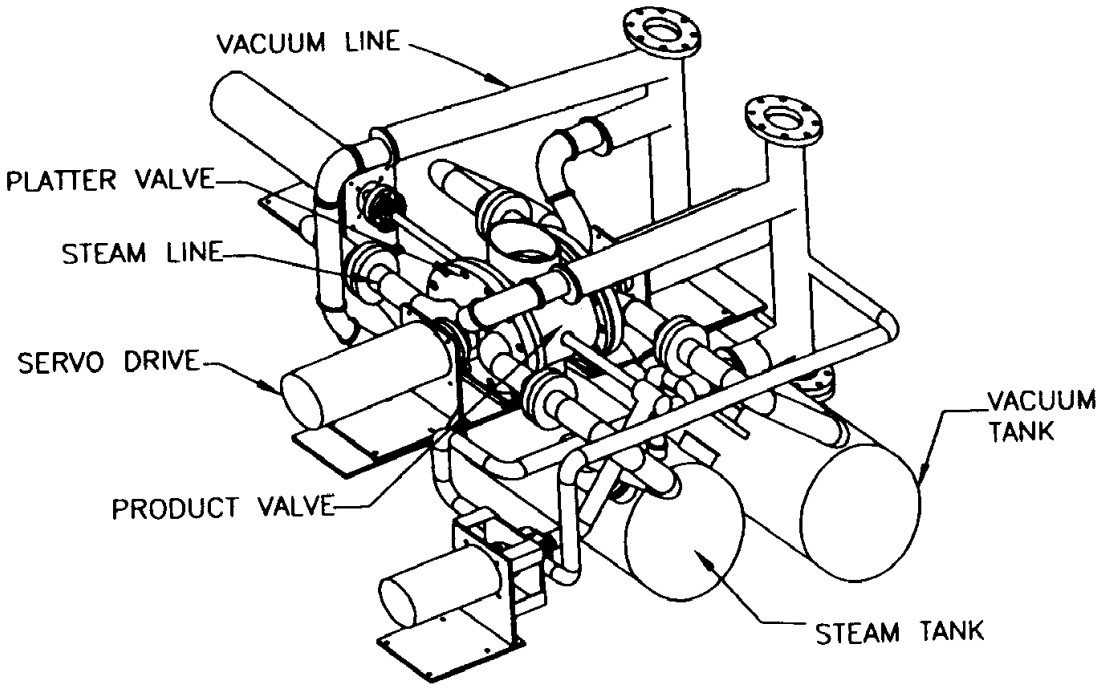

FIG. 1. SCHEMATIC DIAGRAM OF THE SURFACE PASTEURIZATION PROCESSOR

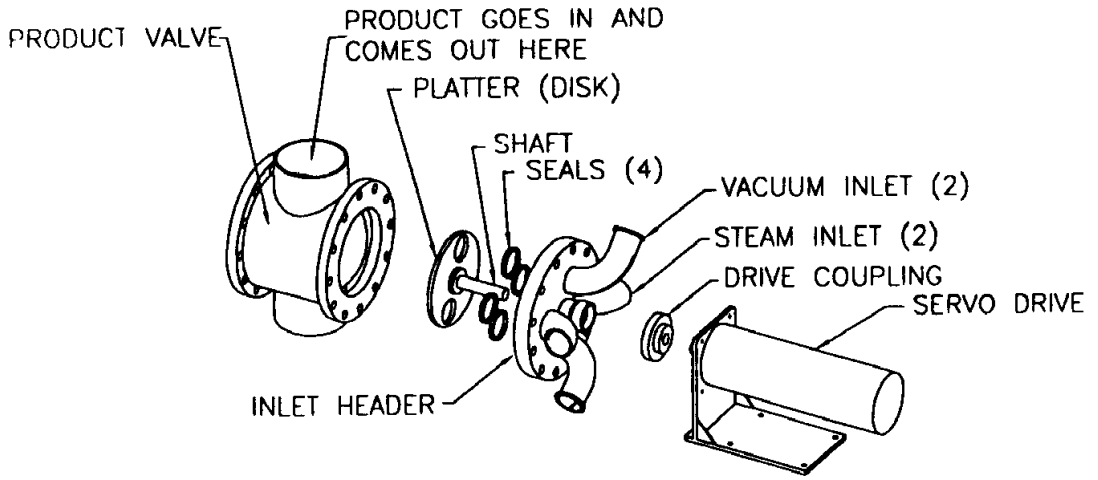

FIG. 2. DETAILS OF THE PRODUCT TREATMENT SECTION OF THE SURFACE PASTEURIZATION PROCESSOR

The nearest poultry processor is at least 2 h away. Warm carcasses would spoil in transit. There is no way to get warm carcasses to the pilot plant without spoilage. This process is not designed to "salvage" spoiled chicken. Therefore, the best approximation was to use chilled carcasses as soon as possible. Undoubtedly, the pores were not fully open. A field unit has been designed and fabricated to go to the poultry processors. There, tests can be made with the pores open. We anticipate the optimum conditions will be the same but the results will be improved.

In the experiments to investigate the different effect on the surface and visceral cavity, Cornish hens were purchased at local supermarkets. Drumsticks were also purchased at local supermarkets. Optimization studies utilized Cornish hens cut in half lengthwise, from breech to neck. These Cornish hens were acquired from a federally inspected commercial processing plant before the chill tank. The carcasses were cooled in ice water with no added chemicals and shipped overnight with ice packs to prevent spoilage.

After processing in the pasteurizer, the chicken samples were placed in sterile plastic bags with Butterfield buffer solution (Difco Laboratories, Detroit, MI) and manually rinsed for 60 s (60 shakes). Whole Cornish hens were rinsed in 200 mL of Butterfield buffer. Fryers cut in half were rinsed in 200 mL of Butterfield buffer. Drumsticks were rinsed in 100 mL of Butterfield buffer and Cornish hens cut in half were rinsed in 200 mL of Butterfield buffer. Aliquots were plated on aerobic plate count 3M Petrifilm™ for aerobic plate count (APC) and on *E. coli* plate count 3M Petrifilm™ for determining coliforms and *E. coli*.

The sponge method (Palumbo *et al.* 1999) was used for experiments in which the cavity was studied separately from the exterior surface. A sterile sponge from a Whirl-pack™ bag dampened with 10 mL of Butterfield buffer (Difco Laboratories, Detroit, MI) was used to swab the exterior surface and cavity of carcasses. The sponge was returned to the bag and stored refrigerated until it was analyzed later the same day.

After addition of 90 mL of Butterfield buffer, the sponge samples were mixed for one minute at normal speed using a stomacher (Stomacher 400, Tekman, Cincinnati, OH). The sponge samples were serially diluted with 0.1% peptone water (Difco Laboratories, Detroit, MI) for *E. coli*. *E. coli* plate counts were obtained, in triplicate, using Pertrifilm™ *E. coli* count plates (3M Microbiology Products, ST. Paul, MN) following the manufacturer's recommended procedures. The Petrifilms™ were manually counted after incubation at 37C for 48 h. The total aerobic counts were obtained on the serially diluted sponge samples using Petrifilm™ Aerobic count plates (3M Microbiology Producers) following the manufacturer's recommended procedures. The Petrifilms™ were manually counted after incubation at 37C for 48 h.

In the first series of commercial tests 5 chicken samples were used for control and for each of 3 sets of the process conditions. In the second series of commercial tests, 20 carcasses were cut in half to give 40 samples. Half of the samples (20 halves) were used as controls and half (20 halves) processed. Both treated samples and controls were chilled for 5 min in cold water after treatment (or lack of treatment) and before analysis. The industry cooperators did this to simulate a chill tank. One bath was used for all the treated samples and another bath for the controls. The water in each bath was not changed. For Table 1, a null hypothesis (Volk 1958) was made on the difference between the mean bacteria kills and zero (H_0; mean = 0). There were 8 replicates for the cavity and for the outer surface samples for run 1. There were 6 replicates for runs 2 to 6. For the 2^3 factorial experimental designs (Davies 1960) of Tables 2-5, treatment samples were taken in triplicate. The data from the factorial designs were analyzed by analysis of variance using the replicate within treatment terms as error terms. Ten control samples were taken.

RESULTS AND DISCUSSION

Commercial Cooperative Tests

The commercial processor who cooperated in the first series of tests supplied Cornish hens exiting the chill tank from a federally inspected processing plant. Control and treated samples were analyzed for total aerobic plate count (APC). There was no statistically significant reduction in bacteria in the test. The controls averaged 3.0 log cfu/mL (SD = 0.29). Treated samples at 144C for 0.2 s had average counts of 3.3 log cfu/mL (SD = 0.48). At 149C for 0.15 s, the counts averaged 2.7 log cfu/mL (SD = 0.40) and, at 154C for 0.05 s, the counts averaged 3.0 log cfu/mL (SD = 0.42). The initial and final vacuum times were 2.0 s. These were preliminary experimental conditions and the results showed that different experimental conditions were required. In retrospect, the process conditions chosen were far from optimal. (As shown later, our current choice of parameter values are 0.1 s initial vacuum time (V1), 0.5 s final vacuum time (V2), 0.1 s steam time and steam temperature of 127-138C).

In all previous work with inoculated chicken, the inoculated section of chicken was excised and stomached to determine the bacteria counts. The whole bird rinse procedure was used in this test. This method tests all surfaces, including the internal cavity. If the surface pasteurizer did not treat the cavity, there would be little or no discernible bacterial reduction. The bacteria count due to the cavity would mask the reduction on the outside. To illustrate this point, consider the surface area of the cavity equal to the outside surface area. (The

assumption of equal surface areas is admittedly a gross simplification for purposes of illustration). Let the bacteria count be 4×10^3 cfu/mL over the entire surface, inside and outside. If the surface pasteurizer killed all the bacteria on the outside and killed none in the cavity, there would be 0 cfu/mL on the outside and 4×10^3 cfu/mL in the cavity after treatment. Whole bird rinse analysis would detect $(0 + 4 \times 10^3)/2$ cfu/mL or 2×10^3 cfu/mL. Before treatment count of 4×10^3 cfu/mL and after treatment count of 2×10^3 cfu/mL would both be considered 3 log within the range of experimental error. (Modifications to the unit to assure adequate treatment of the cavity area are being developed).

TABLE 1.

RESPONSE OF THE CHICKEN CAVITY TO TREATMENT

		Outer Surface			Cavity		
Run	Steam Temp. (C)	Control	Treated	Kill (SD)	Control	Treated	Kill (SD)
		Log cfu/ml			Log cfu/ml		
			E. coli				
1	121 & 157	2.0	<2	— (0.106)	2.5	2.9	— (0.642)
2	116	2.2	<2	0.2 (0.363)	2.7	2.9	— (0.506)
3	116	2.2	<2	0.2 (0.344)	2.7	2.5	0.2 (0.307)
4	116	<2	<2	—	<2	<2	— (0.122)
5	116	<2	<2	—	2.1	2.4	— (0.495)
			Coliforms				
1	121 & 157	3.4	2.2	1.2*** (0.497)	3.6	3.4	0.2 (0.380)
2	116	5.6	5.0	0.6 (0.890)	5.7	5.4	0.3† (0.296)
3	116	4.2	3.6	0.6*** (0.145)	4.5	4.2	0.3** (0.174)
4	116	3.3	2.4	0.9* (0.634)	3.1	2.8	0.3 (0.399)
5	116	2.2	<2	0.2 (0.248)	2.2	2.2	— (0.190)
6	116	3.3	2.3	1.0** (0.498)	2.7	2.7	— (0.525)
			APC				
1	121 & 157	4.4	3.7	0.7** (0.487)	5.0	4.7	0.3 (0.563)
2	116	4.1	3.2	0.9** (0.511)	3.9	3.7	0.2* (0.170)
3	116	2.9	2.5	0.4* (0.320)	3.0	2.8	0.2 (0.429)
4	116	4.1	3.2	0.9** (0.513)	3.4	3.4	— (0.500)

Run 1; 8 samples, V1 (Initial vacuum) = 2.0 s, V2 (Final vacuum) = 2.0 s., Steam time = 0.05, 2.0 s.

Runs 2 – 5; 6 samples, V1 = 2.0 s, V2 = 2.0 s, Steam time = 1.0 s.

Run 6; 6 samples, V1 = 1, 5, 10 s, V2 = 1, 5, 10 s, Steam time = 1.0 s.

Significant differences represented by; $^{*}p \leq 0.05$ $^{**}p \leq 0.01$ $^{***}p \leq 0.001$ $^{\dagger}p \leq 0.10$.

A second series of commercial tests were scheduled with another poultry processor. Because of the previous study, it was decided to process chicken halves to eliminate the masking effect of the cavity. After overnight delivery, according to the industry cooperators, the counts were abnormally high, not representative of prechill birds. Carcasses, as received, had mean log counts of 6.1 cfu/mL for APC, 4.7 cfu/mL for coliforms, and 4.2 cfu/mL for *E. coli*. Half of the samples (20 halves) were used as controls and half (20 halves) processed at 138C for 0.1 s. Data analysis showed a significant ($p \leq 0.05$) reduction in bacteria due to treatment. Bacteria kills due to treatment were 0.8 log cfu/mL for APC, 0.4 log cfu/mL for coliforms, and 0.4 log cfu/mL for *E. coli*.

Processing chicken halves exposed a potential problem. The cut surface exhibited thermal damage and a thin white film formed at the cut. The film could be wiped off. The intact meat and skin, on the same sample, was virtually unaffected. No problem is anticipated when processing uncut carcasses; but cut pieces may present difficulties yet to be addressed.

Cavity Studies

When the whole carcasses were treated, there was no statistically significant bacteria kill. When chicken halves were treated (no cavity present), there was statistically significant bacteria kill. These tests suggested that the surface pasteurization treatment did not reach the visceral cavity. A series of experiments were made in which the surface and cavity of carcasses purchased at the supermarket were sampled, before and after treatment using the sponge method of analysis (Palumbo *et al.* 1999). Each sample was tested on the surface and in the cavity on one side before treatment. Each sample was tested on the exterior surface and in the cavity on the opposite side after treatment.

Table 1 lists the results for six experiments. Since we were more concerned with detecting a difference of treatment between the cavity and the surface, we ignored cooking or thermal damage. Therefore, most of the data were collected at more severe conditions than would be used in actual processing. For example, most steam times were 1.0 s whereas the preferred time is 0.1 s. These experiments were performed before optimum conditions had been established.

As expected, because these carcasses were bought at a local supermarket, the counts were lower than would normally be expected from carcasses pulled before the chill tank. Initial counts for *E. coli* were less than log 3 cfu/mL, Table 1. After treatment, *E. coli* were at or below log 2 cfu/mL on all surface samples. However, the cavity showed virtually no reduction in bacteria and the counts in the cavity were, with one exception, above log 2 cfu/mL.

As listed on Table 1, coliform counts were higher, ranging as high as log 5.7 cfu/mL, which permitted statistical comparison between the outside surface

and the cavity treatments. Four of the six outside surfaces showed significant kills ($p \leq 0.05$). Only one cavity mean was significant ($p \leq 0.05$) and one possibly significant ($p \leq 0.1$). Also, note the coliforms for the treated surface samples were consistently lower than the treated cavity samples. Surface samples experienced an average bacteria reduction of 0.8 log cfu/mL. There was little reduction associated with the cavity.

There were similar results for APC, Table 1. The surface samples always had lower counts than the cavity samples. All four of the outside surfaces showed significant kills of $p \leq 0.05$. Only one cavity mean was significant ($p \leq 0.05$). The average kill on the surface was 0.7 log cfu/mL whereas there was little kill in the cavity. These results confirm our suspicion that the cavity was minimally exposed to the surface pasteurization treatment during the verification experiments.

Optimization Experiments

The verification experiments were continued using chicken halves to eliminate masking due to the cavity. A series of experiments were made using 2^3 experimental designs to determine the effect of vacuum time, steam time, and temperature using chicken taken before the chill tank from federally inspected processing plants. The samples were pulled before the chill tank so the bacteria counts would be relatively high and because the opinion of industry is that the processor would be used in this location. Unfortunately, there are no chicken processing plants close to our pilot plant but it was important to transport the carcasses to the pilot plant with minimum bacteria growth to prevent spoilage. Carcasses were removed from the prechill line, chilled in a tub of ice water for about 45 min (no Cl_2 added as in the standard chill tank) and shipped overnight with ice packs. This unfortunately prevented testing warm carcasses with the pores still open but did eliminate the Cl_2 treatment from the chill tank. Under these conditions, the carcasses had very low bacteria counts. Ideally, we would like to study the effect of treatment on *E. coli*. Untreated control samples had an average bacteria count based on ten samples, of 1.5 log cfu/mL (SD = 0.67) for *E. coli*. Coliforms averaged less than 2 log cfu/mL (SD = 0.38). APC offered reasonably high counts for study. Unfortunately, the component bacteria in APC were unknown, almost certainly varied from carcass to carcass, and were probably spoilage bacteria and not pathogens.

Our previous work, using inoculated chicken parts purchased at the supermarket, produced no optimum conditions. This suggested that the process response surface was on a ridge or plateau. In this study a fairly wide spread in variables was chosen to increase the chance of a response. There were constraints. Above 138C subjective evaluations indicated there is too much thermal damage. Therefore, 138C was chosen as the upper limit for tempera-

ture. The lower limit of 110C was the lowest temperature that could be controlled reliably. Table 2 lists the experimental design and the analysis of variance of the responses. Not shown in the table are the subjective evaluations of thermal damage. A final vacuum time of 0.1 s was insufficient to re-cool the product and prevent some thermal damage. Other subjective experiments showed an acceptable final vacuum time for cooling is 0.5 s (unpublished data).

Table 2 shows the carcasses had relatively low bacteria counts, *E. coli* and coliforms were less than 2 log cfu/mL and APC was 3 log cfu/mL. The only statistically ($p \leq 0.05$) significant effect was due to independent variable C, temperature, for all three response variables. The treated carcasses felt warm, but not hot, when removed from the treatment chamber. However, they were

TABLE 2.

2^3 EXPERIMENTAL DESIGN AND ANALYSIS OF VARIANCE USING CHICKEN HALVES

	Factor Levels	
Experimental Factors	—	+
A	0.1 s	0.5 s
B	0.1 s	0.4 s
C	110 C	138 C

A = initial vacuum time.

B = steam time.

C = steam temperature.

	APC			*E. coli*			Coliforms		
Experimental Factors and Interactions	Mean, Log cfu/ml	Mean Square	F value	Mean, Log cfu/ml	Mean Square	F value	Mean, Log cfu/ml	Mean Square	F value
A	3.92	0.219	1.43	1.29	0.001	0.01	1.52	0.017	0.18
B	3.68	0.038	0.25	1.32	0.038	0.49	1.52	0.002	0.02
AB	3.54	0.001	0.00	1.63	0.293	3.78	1.71	0.157	1.70
C	2.51	9.920	65.11***	1.17	1.013	13.07**	1.31	0.944	10.21**
AC	2.29	0.014	0.09	0.82	0.067	0.87	1.17	0.000	0.00
BC	2.76	0.555	3.64	0.94	0.027	0.35	1.24	0.005	0.05
ABC	2.50	0.001	0.00	1.07	0.003	0.03	1.26	0.040	0.43
Error		0.152			0.077			0.092	

Significant differences represented by; *$p \leq 0.05$ **$p \leq 0.01$ ***$p \leq 0.001$.

Treatment samples consisted of 3 replicates.

Control, APC (10 replicates) = 3.27 log cfu/ml (SD = 0.39).

Control, *E. coli* (10 replicates) = 1.48 log cfu/ml (SD = 0.67).

Control, Coliforms (10 replicates) = 1.92 log cfu/ml (SD = 0.38).

Mean Square is the measure of variability attributed to the experimental factor or interaction.

cooling very rapidly. The carcasses cooled to room temperature within 30 s of removal from the chamber. There was some thermal damage. This indicated increased evaporative cooling was needed. Although steam and vacuum times were not statistically significant, the responses suggested the shorter times were better. The mean counts at high and low levels of factor C were 2.51 and 3.80 log cfu/mL for APC, 1.00 and 1.41 log cfu/mL for *E. coli* and 1.24 and 1.64 log cfu/mL for coliform.

The design was repeated as shown in Table 3; but with the final vacuum time set at 0.5 s. At this final vacuum time there was minimal thermal damage and the carcasses did not feel as warm to the touch. The APC response confirmed variable C, temperature, was statistically significant. *E. coli* and coliform responses were not significant. The interaction terms AB (initial vacuum time and steam time) and BC (steam time and temperature) were significant for APC. The mean counts of treated samples at high and low levels of factor C were 3.14 and 3.49 log cfu/mL for APC, 1.81 and 1.72 log cfu/mL for *E. coli* and 1.88 and 1.90 log cfu/mL for coliform.

Aside from the differences in the carcasses because they were from different batches, the major difference in the two designs was the final vacuum time. Therefore, the two experiments were combined into a blocked 2^4 design, with the ABCD interaction confounded, to determine if the final vacuum time was significant. Table 4 shows the experimental design and the analysis of variance of the responses. As expected the analysis of variance shows significant effects for factor C, temperature, for the APC and coliform responses. The analysis also indicated significant effects due to factor D, final vacuum time, for *E. coli* and coliform but not for APC. Both *E. coli* and coliform responses were significantly higher at the higher level of factor D. The mean counts at high and low levels of factor D were 1.76 and 1.21 log cfu/mL for *E. coli* and 1.89 and 1.44 log cfu/mL for coliform. There were also significant interactions. For APC, factor BC, steam time and temperature interaction, was significant and CD, steam temperature and final vacuum time, was significant. Factor CD, steam temperature and final vacuum time, was significant for *E. coli*. To prevent thermal damage, a final vacuum time of 0.5 s was chosen. However, continuing optimization studies are planned.

Another design was made to see if milder conditions could be used, Table 5. In the design, the higher steam temperature was set to 127C and the lower initial vacuum time and lower steam times set to the shortest possible time in the processor, 0.004 s. Final vacuum time stayed at 0.5 s to assure an acceptable product. The analysis of variance showed there was a significant effect due to factor C, temperature, for APC. Both factors A, initial vacuum time, and C, temperature, were significant for *E. coli* and coliform. These results indicate the initial vacuum time of 0.004 s is too short to sufficiently remove the air layer form the surface of the carcass and the initial vacuum time should be 0.1 s. The

mean counts of treated samples at high and low levels of factor C were 2.98 and 3.49 log cfu/mL for APC, 1.61 and 1.96 log cfu/mL for *E. coli* and 1.97 and 2.31 log cfu/mL for coliform. The mean counts at high and low levels of factor A were 3.15 and 3.32 log cfu/mL for APC, 1.57 and 1.90 log cfu/mL for *E. coli* and 1.98 and 2.30 log cfu/mL for coliform.

TABLE 3.

2^3 EXPERIMENTAL DESIGN AND ANALYSIS OF VARIANCE USING CHICKEN HALVES AT INCREASED FINAL VACUUM TIME OF 0.5 S

Experimental Factors	Factor Levels	
	—	+
A	0.1 s	0.5 s
B	0.1 s	0.4 s
C	110 C	138 C

A = initial vacuum time.

B = steam time.

C = steam temperature.

	APC			*E. coli*			Coliforms		
Experimental Factors and Interactions	Mean, Log cfu/ml	Mean Square	F value	Mean, Log cfu/ml	Mean Square	F value	Mean, log cfu/ml	Mean Square	F value
A	3.80	0.009	0.08	1.84	0.105	0.63	1.92	0.000	0.00
B	3.61	0.056	0.48	1.49	0.019	0.11	1.86	0.036	0.27
AB	3.10	0.577	4.99*	1.81	0.006	0.04	1.92	0.001	0.01
C	2.73	0.756	6.55**	1.64	0.046	0.27	1.81	0.002	0.01
AC	3.08	0.084	0.72	1.73	0.038	0.22	1.77	0.012	0.09
BC	3.39	0.821	7.11**	1.92	0.211	1.26	2.00	0.063	0.05
ABC	3.35	0.077	0.67	1.93	0.032	0.19	1.94	0.001	0.01
Error		0.116						0.133	

Significant differences represented by; $^{*}p \leq 0.05$ $^{**}p \leq 0.01$ $^{***}p \leq 0.001$.

Treatment samples consisted of 3 replicates.

Control, APC (10 replicates) = 3.92 log cfu/ml (SD = 0.256).

Control, *E. coli* (10 replicates) = 2.77 log cfu/ml (SD = 0.550).

Control, Coliforms (10 replicates) = 2.80 log cfu/ml (SD = 0.561).

Mean Square is the measure of variability attributed to the experimental factor or interaction.

TABLE 4.

BLOCKED 2^4 EXPERIMENTAL DESIGN AND ANALYSIS OF VARIANCE USING CHICKEN HALVES

Experimental Factors	Factor Levels —	Factor Levels +
A	0.1 s	0.1 s
B	0.1 s	0.1 s
C	110 C	138 C
D	0.1 s	127 C

A = initial vacuum time.

B = steam time.

C = steam temperature.

D = final vacuum time.

Experimental Factors and Interactions	APC Mean, Log cfu/ml	APC Mean Square	APC F value	*E. coli* Mean, Log cfu/ml	*E. coli* Mean Square	*E. coli* F value	Coliforms Mean, log cfu/ml	Coliforms Mean Square	Coliforms F value
A	2.51	0.070	0.52	1.17	0.046	0.37	1.31	0.011	0.09
B	3.10	0.001	0.01	1.81	0.055	0.45	1.92	0.011	0.09
AB	3.08	0.309	2.31	1.73	0.193	1.57	1.77	0.089	0.79
C	3.46	8.077	60.30***	1.73	0.314	2.567	1.91	0.515	4.56*
AC	3.39	0.015	0.11	1.92	0.103	0.84	2.00	0.007	0.06
BC	4.06	1.364	10.18**	1.39	0.043	0.35	1.81	0.051	0.46
ABC	3.61	0.032	0.24	1.49	0.008	0.07	1.86	0.028	0.24
D	2.50	0.296	2.21	1.07	3.696	30.14***	1.26	2.399	21.26***
AD	3.92	0.158	1.18	1.29	0.060	0.49	1.52	0.007	0.06
BD	3.35	0.093	0.69	1.93	0.002	0.01	1.94	0.028	0.24
ABD	2.76	0.269	2.00	0.94	0.106	0.87	1.24	0.068	0.60
CD	3.80	2.599	19.41***	1.84	0.745	6.07	1.92	0.431	3.82
ACD	3.54	0.083	0.62	1.63	0.002	0.02	1.71	0.005	0.04
BCD	2.73	0.013	0.10	1.64	0.195	1.59	1.81	0.017	0.15
Error		0.1339			0.1227			0.1128	

Significant differences represented by; *$p \leq 0.05$ **$p \leq 0.01$ ***$p \leq 0.001$.

Treatment samples consisted of 3 replicates.

Control, APC (20 replicates) = 3.59 log cfu/ml (SD = 0.464).

Control, *E. coli* (20 replicates) = 2.12 log cfu/ml (SD = 0.896).

Control, Coliforms (20 replicates) = 2.36 log cfu/ml (SD = 0.650).

Mean Square is the measure of variability attributed to the experimental factor or interaction.

TABLE 5.

2^3 EXPERIMENTAL DESIGN AND ANALYSIS OF VARIANCE USING CHICKEN HALVES AT MILDER CONDITIONS

	Factor Levels	
Experimental Factors	—	+
A	0.004 s	0.1 s
B	0.004 s	0.1 s
C	110 C	127 C

A = initial vacuum time.

B = steam time.

C = steam temperature.

	APC			*E. coli*			Coliforms		
Experimental Factors and Interactions	Mean, Log cfu/ml	Mean Square	F value	Mean, Log cfu/ml	Mean Square	F value	Mean, Log cfu/ml	Mean Square	F value
A	3.44	0.186	2.67	1.64	1.063	10.24**	2.16	0.605	7.37*
B	3.49	0.103	1.48	2.39	0.046	0.44	2.67	0.012	0.14
AB	3.29	0.015	0.21	1.70	0.074	0.71	2.05	0.128	1.55
C	2.98	1.556	22.38***	1.68	0.746	7.19*	2.03	0.725	8.83**
AC	3.04	0.038	0.54	1.53	0.158	1.53	1.91	0.063	0.77
BC	3.08	0.033	0.47	1.80	0.038	0.36	2.12	0.015	0.18
ABC	2.83	0.069	1.00	1.43	0.000	0.00	1.81	0.018	0.21
Error		0.070			0.104			0.082	

Significant differences represented by; $^{*}p \leq 0.05$ $^{**}p \leq 0.01$ $^{***}p \leq 0.001$.

Treatment samples consisted of 3 replicates.

Control, APC (10 replicates) = 3.34 log cfu/ml (SD = 0.373).

Control, *E. coli* (10 replicates) = 2.34 log cfu/ml (SD = 0.384).

Control, Coliforms (10 replicates) = 2.62 log cfu/ml (SD = 0.318).

Mean Square is the measure of variability attributed to the experimental factor or interaction.

Based on these factorial design results an initial vacuum time of 0.1 s was decided upon. Except for interaction terms, the steam time was not significant in any design. Therefore a steam time of 0.1 was chosen. Steam temperature was significant at both 127C and 138C. A final vacuum time of 0.1 s is too short for acceptable evaporative cooling. The final vacuum time was chosen at 0.5 s, which may be somewhat high. The optimum processing conditions chosen were; initial vacuum = 0.1 s, steam time = 0.1 s, steam temperature = 127-138C, and final vacuum time = 0.5 s. This is not a true optimum but is sufficiently close to use in further research to develop a modification for cavity treatment. Final optimization will be performed during in-plant testing.

In a follow-up series of experiments to test the previous findings, packages of six-drumsticks were bought at the supermarket and each package processed separately, three as controls and three treated. Drumsticks eliminated the difficulties with the cavity and cut surfaces. Only temperature was varied. Supermarket drumsticks had such low *E. coli* and coliform counts, only APC counts were determined. Table 6 lists the results. In all cases, treated samples had lower APC levels than controls. Bacteria reduction was statistically significant ($p \leq 0.05$) in the range of 127-138C.

TABLE 6.

RESPONSE USING CHICKEN DRUMSTICKS

		APC, Log cfu/mL (Whole Bird Method, n = 3)		
Pkg	Temp. (C)	Control (SD)	Treated (SD)	Kill
A	116	2.1 (0.070)	2.0 (0.101)	0.1
B	121	2.1 (0.214)	1.8 (0.320)	0.3
C	121	1.8 (0.084)	1.5 (0.237)	0.3
D	127	3.3 (0.152)	2.0 (0.405)	1.2*
E	127	2.1 (0.075)	1.6 (0.247)	0.5*
F	132	2.1 (0.017)	1.2 (0.316)	0.9*
G	132	2.4 (0.038)	1.7 (0.346)	0.7*
H	138	2.2 (0.060)	1.6 (0.247)	0.7*

Initial vacuum = 0.1 s, Final vacuum = 0.5 s, Steam time = 0.1 s.

Significant difference represented by $^{*}p \leq 0.05$.

The surface pasteurizer kills naturally occurring bacteria on the surface of chicken. Based on results with chicken halves and drumsticks, treated samples had *E. coli* counts consistently below log 2 cfu/mL. Bacteria kills for *E. coli*, coliforms, and APC generally ranged from 0.6 to 1.0 log cfu/mL. This was for chicken that had been chilled and shipped overnight or purchased at the supermarket. The current unit does not adequately treat the cavity but a modified process is being developed to accommodate the cavity. The best operating parameters found are; 0.1 s initial vacuum (V1), 0.5 s final vacuum (V2), 0.1 s steam time and steam temperature of 127-138C.

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